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SATELLITE-DERIVED MOISTURE-BOGUSING PROFILES FOR THE NORTH ATLANTIC OCEAN

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A set of 12 vertical profiles of relative humidity for use in satellite bogusing of moisture into numerical weather prediction model initial analysis is presented for the North Atlantic Ocean region. The profiles are based on a satellite image cloud classification scheme applied to a concurrent data set of satellite images and upper-air soundings. Relative humidity profile composites and statistical significance tests are presented for each cloud category. Sources of error in the compositing process are discussed, and possible improvements are suggested.

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CONTENTS

1. INTRODUCTION

Numerical weather prediction models are highly dependent on analyses of initial atmospheric conditions in order to accurately predict future conditions. In general, the more accurate these initial analyses, the more accurate the prediction. The analyses are usually good over land areas due to the relatively dense networks of surface and upper-air observation stations. Unfortunately, over the oceans there are very few of these conventional observations. Thus the accuracy of the model initial analyses for the ocean areas is often questionable.

Due to ~~this~~ the lack of observational data over oceans, a technique was created which uses meteorological satellite image analysis to better assess the spatial distribution of moisture in the atmosphere. The technique, called "moisture bogusing," has been used ~~utilized~~ since the early 1970's by the National Meteorological Center (NMC) to improve their model initialization (Chu, 1977; Smigielski et al., 1982; Timchalk, 1986). The technique is used ~~utilized~~ by assigning one of a number of previously computed vertical moisture profiles to different areas on a satellite image, gridding the analysis, and incorporating these profiles into model initialization. The vertical moisture profiles are computed by averaging soundings of relative humidity for different synoptic scale cloud patterns observed on satellite imagery. The importance of moisture bogusing in the numerical forecasting of precipitation was demonstrated by Lyons (1986a), and modifications to NMC's moisture profiles were suggested in Lyons (1986b).

This report presents the results of an ongoing study funded by the Naval Enviromental Prediction Research Facility (NEPRF) to establish sets of moisture bogusing profiles for different ocean areas. The results presented here are for the North Atlantic Ocean. The paper proceeds as follows: Section 2 describes the data and procedures, Section 3 describes the results, Section 4 contains discussion and suggestions, and Section 5 is a summary.

2. DATA AND PROCEDURES

In order to determine a set of vertical moisture profiles for the North Atlantic, soundings of relative humidity versus pressure were matched with concurrent visual and infrared Northern Hemisphere satellite image mosaics taken from the NOAA-2 polar orbiting satellite. A total of 471 soundings, taken from four ocean weather ships and one island station, for the months of January, July, and October 1974 were used in creating the bogusing profiles. Table 1 gives the station names, locations, number of soundings by month, and total number of soundings. Relative humidity values were computed from the upper-air soundings of temperature and dewpoint at mandatory and significant pressure levels. These values were interpolated to 19 pressure levels ranging from 1000 to 100 mb at 50 mb increments. Missing

Table 1.
Number of Observations

Station	Position	Jan.	Jul.	Oct.	Total
Ship H	38 N 72 W	40	0	0	40
Ship I	60 N 19 W	29	30	33	92
Ship J	53 N 19 W	38	36	39	113
Ship K	45 N 16 W	41	43	46	130
Bermuda	32 N 65 W	34	31	31	96
		182	140	149	471

values above 300 mb were set to 5 percent.

A scheme different from the NMC cloud pattern categorization scheme was created in order to simplify the subjective analysis. This categorization scheme is presented in Table 2. The first 11 categories are the identifiable categories running roughly from dry to moist. Category 12 is a composite of all cases on which the analyst was undecided. Category 13 is the composite ensemble of all 471 soundings used in this study.

Each sounding was assigned to one of the first 12 categories based on a subjective analysis of the corresponding satellite image(s). Composites and 67 percent confidence limits were computed for each category. Significance tests using the Wilcoxon rank-sum test were made to determine the statistcal significance of the individual category's relative humidity differences from

Table 2.
Cloud Pattern Classification Scheme

Category #	Description
1	Clear
2	Stratus
3	Stratocumulus
4	Open-celled cumulus
5	Open-celled cumulonimbus
6	Altocumulus (chaotic)
7	Altostratus (organized)
8	Thin cirrus
9	Thick cirrus
10	Low, mid, and high clouds (chaotic)
11	Low, mid, and high clouds (organized)
12	Undecided
13	Ensemble

the ensemble. These results are presented in the following section.

3. RESULTS

The results of the compositing are presented in Table 3. The composites are also presented graphically in Figs. 1-13 with 67 percent confidence limits, and level by level significance

Table 3.
Relative Humidity Composites (%)

Press. (mb)	Category												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1000	76	90	81	74	73	81	82	82	84	80	85	79	80
950	75	81	82	78	75	88	90	80	81	81	87	79	80
900	66	66	72	75	75	90	92	72	80	79	85	73	74
850	49	53	57	65	71	71	88	60	67	73	80	65	64
800	44	49	47	56	65	65	78	55	61	65	79	57	56
750	42	42	44	49	61	62	69	50	64	59	80	52	52
700	40	37	39	41	55	63	67	46	67	57	75	48	48
650	38	35	37	36	52	63	62	44	70	55	75	46	45
600	36	31	32	34	51	53	64	42	64	56	75	42	43
550	30	30	33	32	46	53	54	43	70	52	71	41	41
500	24	31	33	29	33	46	45	44	67	48	66	38	39
450	21	32	31	26	18	36	44	46	62	48	54	34	36
400	20	28	28	18	8	33	33	40	49	42	42	30	30
350	25	26	25	13	5	29	24	30	26	28	23	24	23
300	13	13	9	7	5	5	9	9	12	8	9	8	9
250	5	5	5	5	5	5	5	5	9	5	5	5	5
200	5	5	5	5	5	5	5	5	5	5	5	5	5
150	5	5	5	5	5	5	5	5	5	5	5	5	5
100	5	5	5	5	5	5	5	5	5	5	5	5	5

values which compare the category composite to the rest of the sample. Figure 1 shows the ensemble (category 13) with 67 percent confidence limits for each level. The confidence limits for this and all other categories were computed using nonparametric statistics. Nonparametric statistics were used because they do not need a normally distributed sample to be valid. This choice seemed appropriate when dealing with relative humidity values with limiting values of 0 and 100 percent and asymmetric distributions. Confidence limits computed in this manner represent the upper and lower bounds of the middle two-thirds of the relative humidity values observed at that level.

The number of soundings in each category is given in the top right hand corner of the figures as "N=" followed by two numbers. The first number is the total number of soundings. The second number, within the parenthesis, is the number of soundings with data above 400 mb. The reason for this difference is that the data base of soundings from Ship H and Bermuda had no data above 400 mb.

Significance values were only computed for the first 15 pressure levels (1000-300 mb) due to the lack of significant variability in the data above 300 mb. The significance values represent the probability that the individual category versus the ensemble relative humidity rank-sum discrepancies was due to chance. For example, a value of 0.05 (denoted by the dashed line

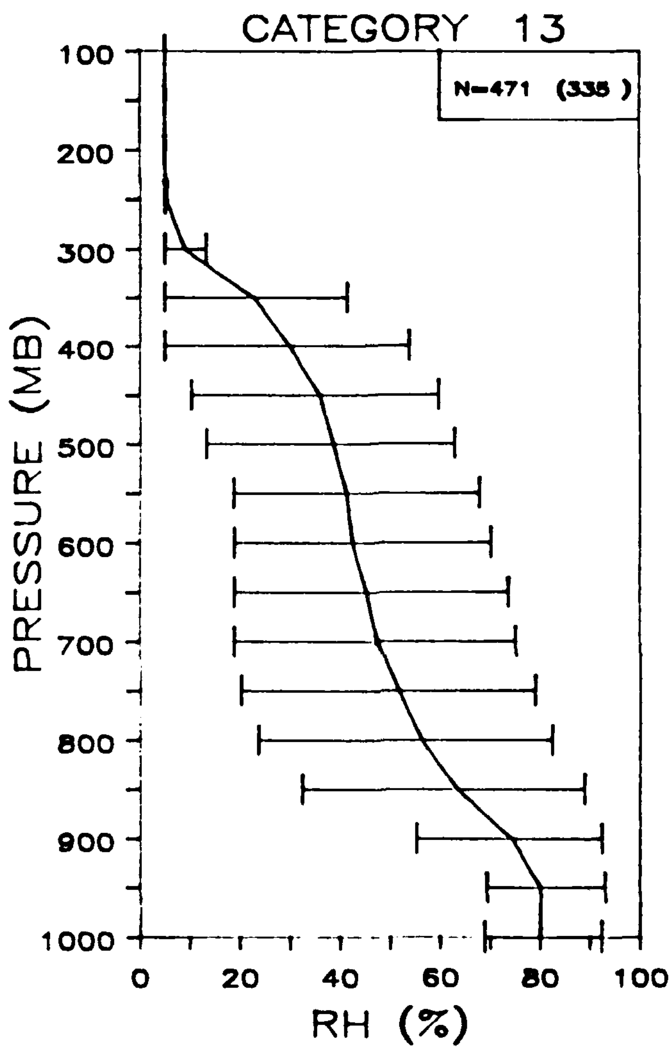

FIG. 1. Relative humidity composite with 67 percent confidence limits for Category 13 (sample ensemble).

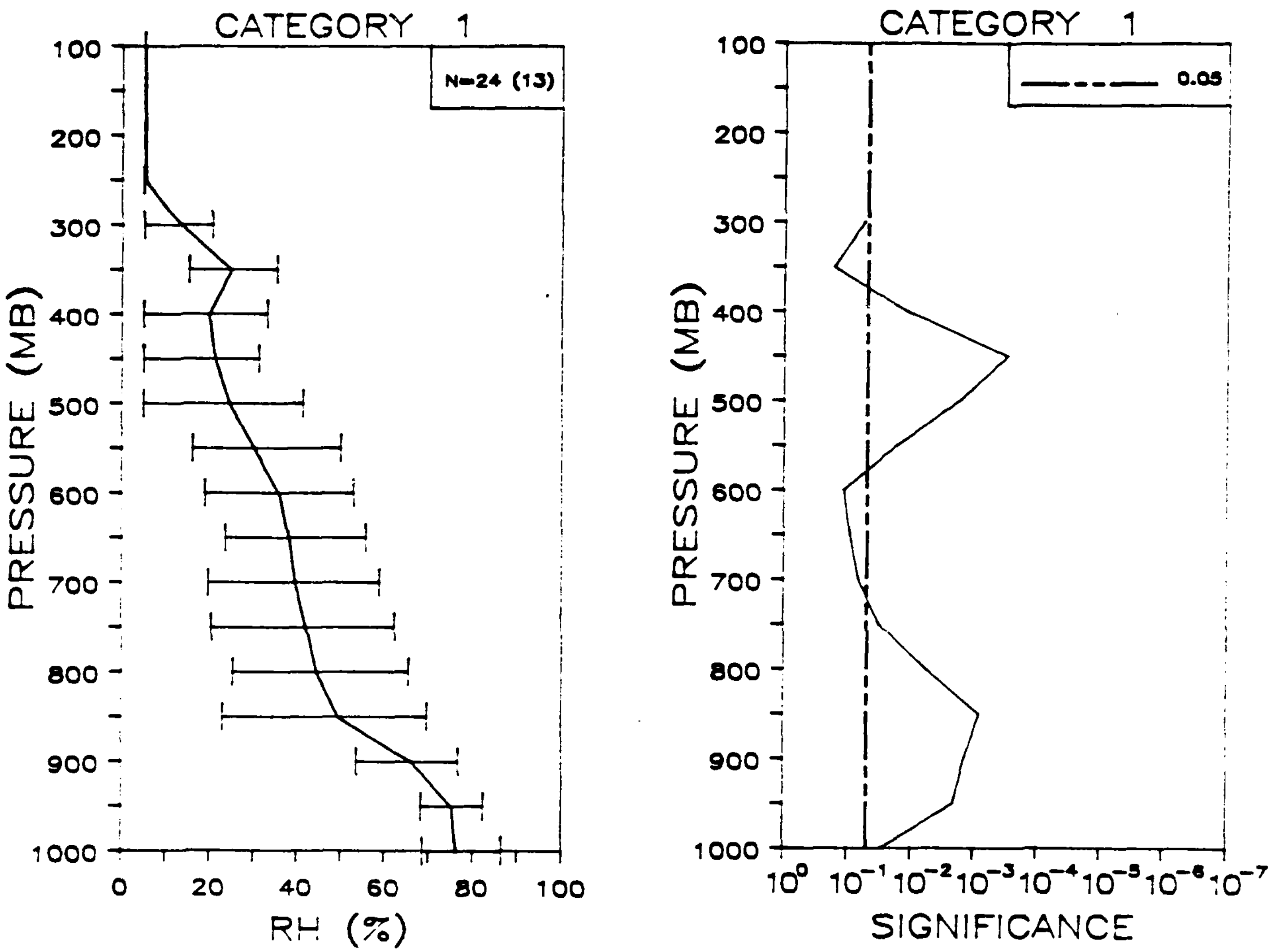

FIG. 2. Relative humidity composite with 67 percent confidence limits and level by level significance values for Category 1 (clear).

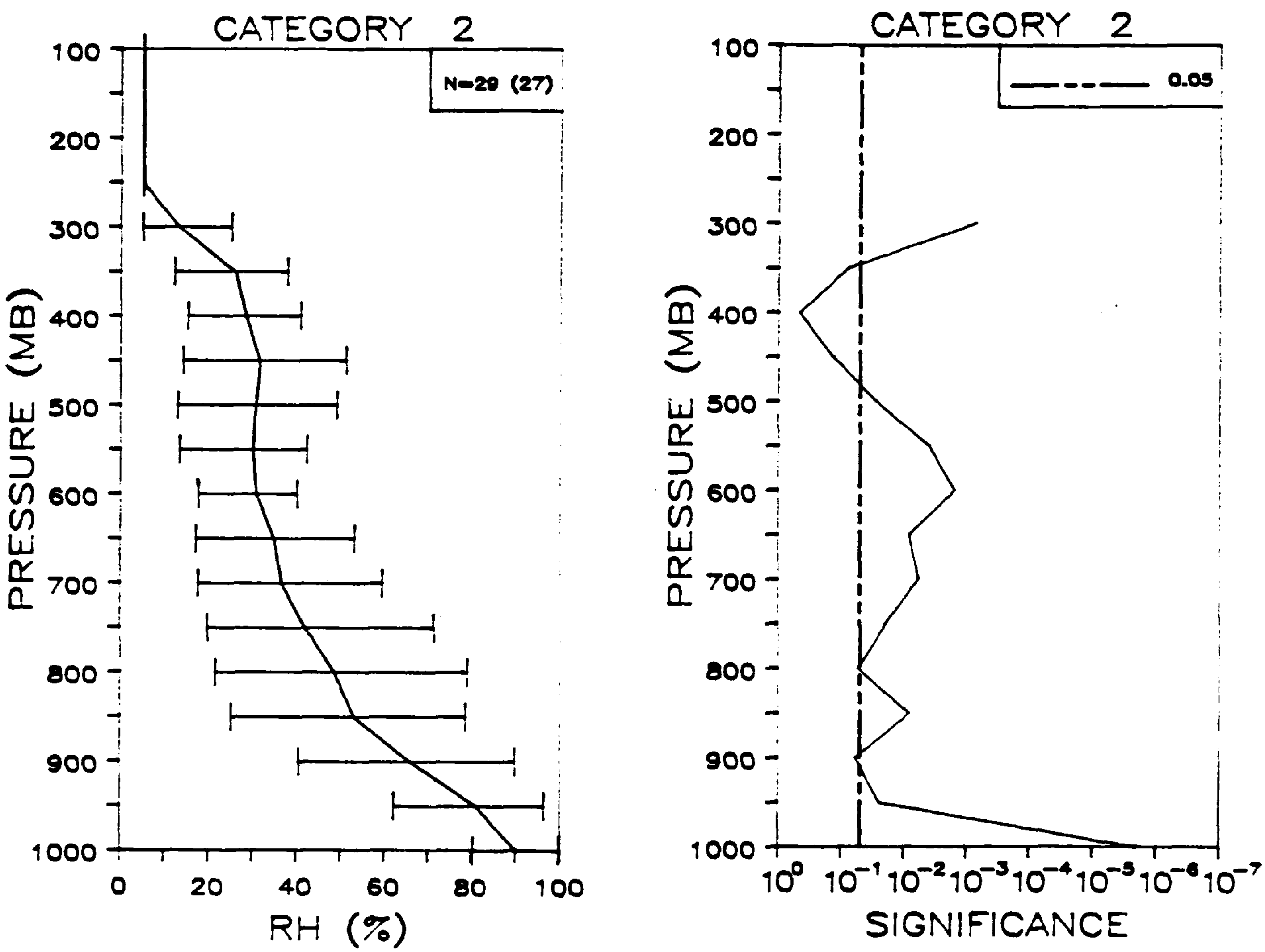

FIG. 3. Same as in Fig. 2 but for Category 2 (stratus).

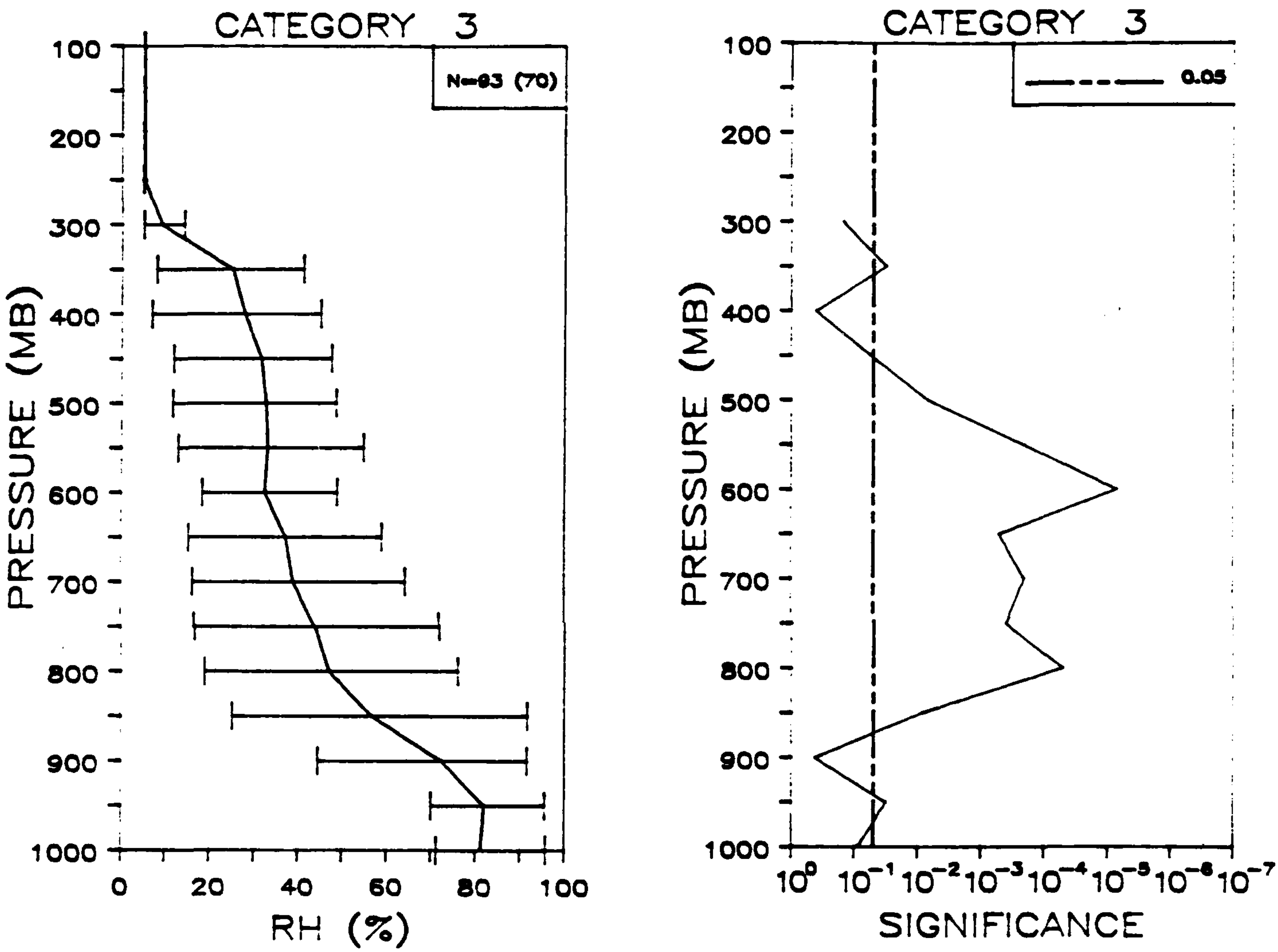

FIG. 4. Same as in Fig. 2 but for Category 3 (stratocumulus).

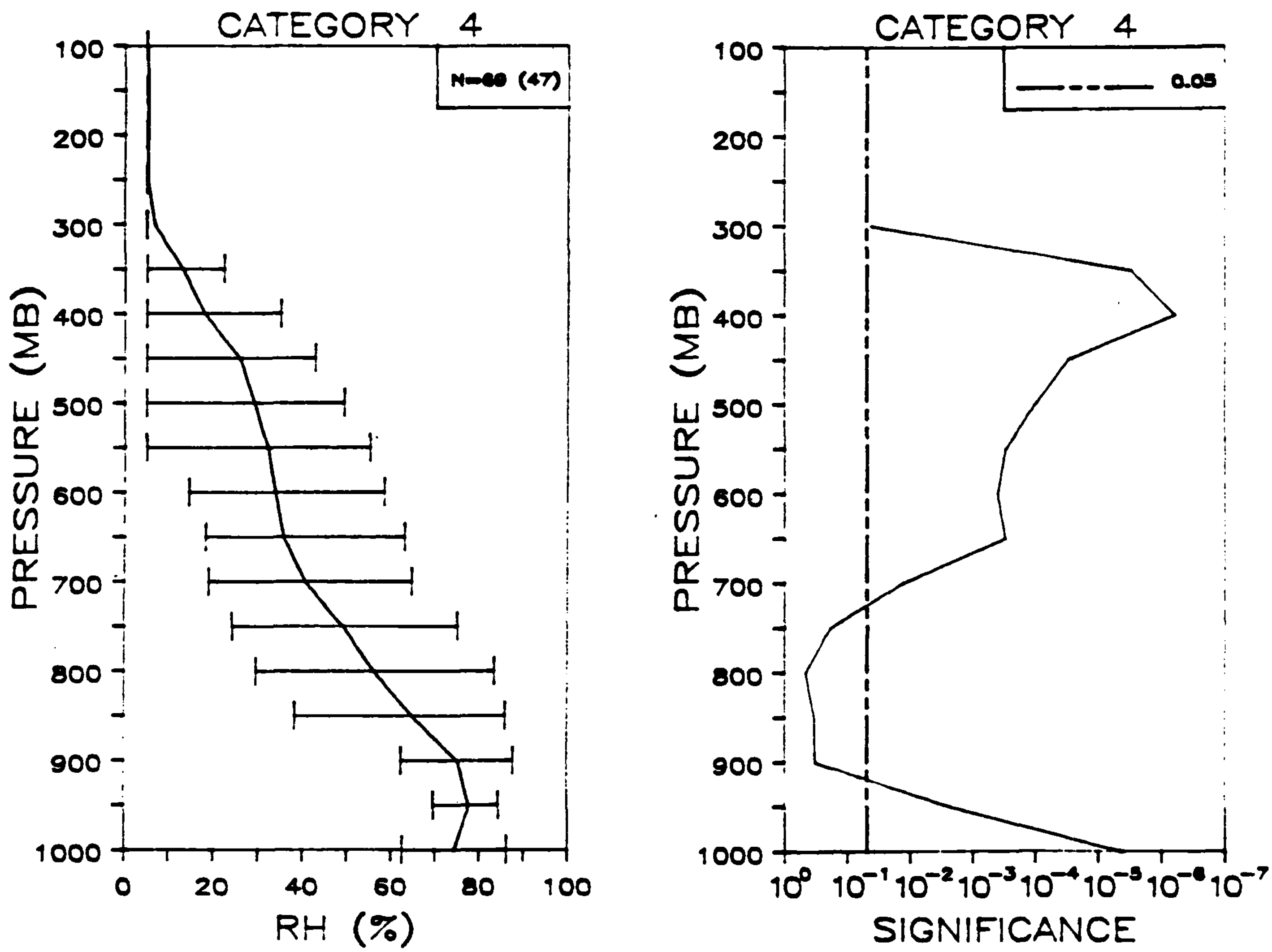

FIG. 5. Same as in Fig. 2 but for Category 4 (open-celled cumulus).

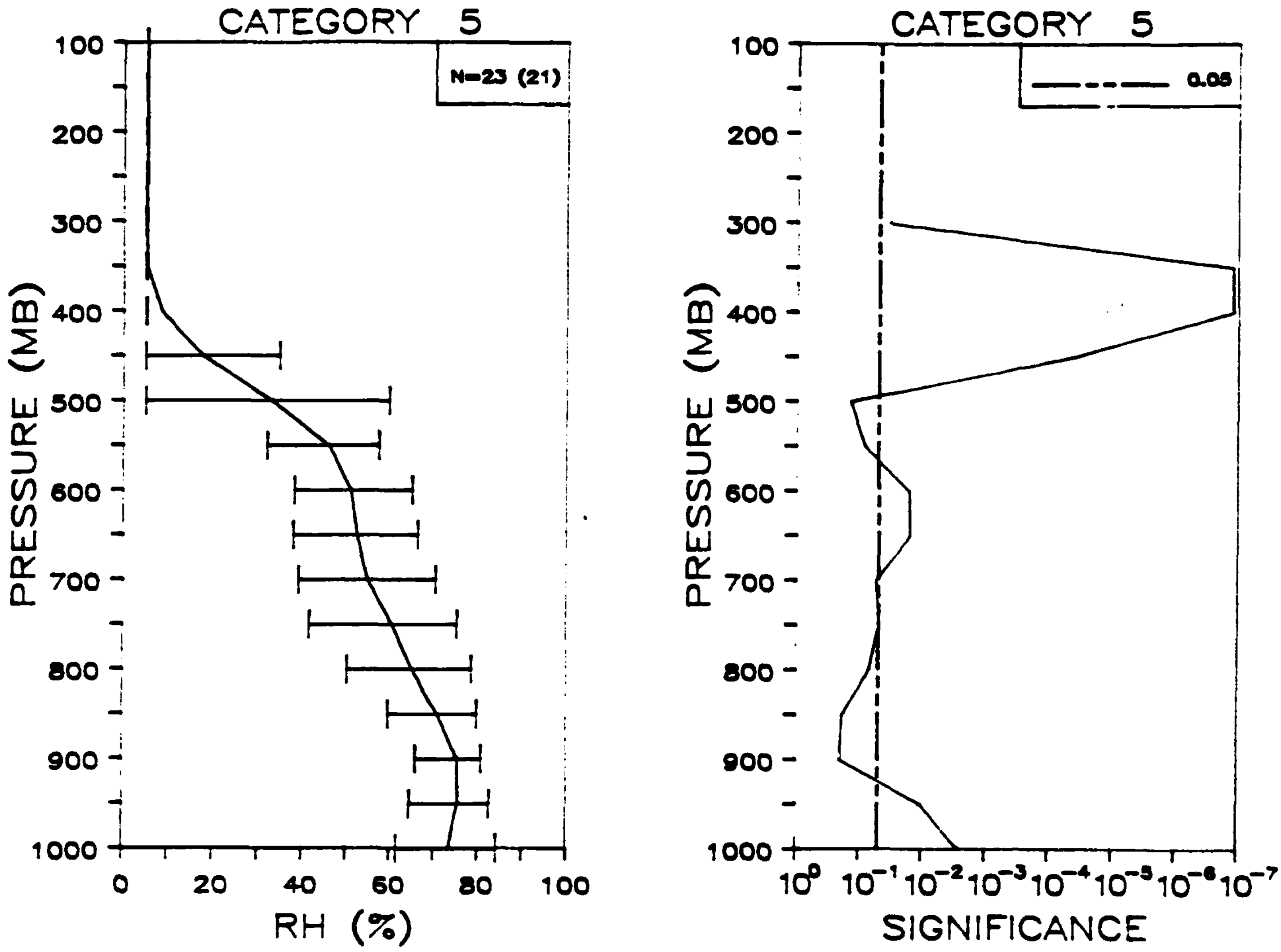

FIG. 6. Same as in Fig. 2 but for Category 5 (open-celled cumulonimbus).

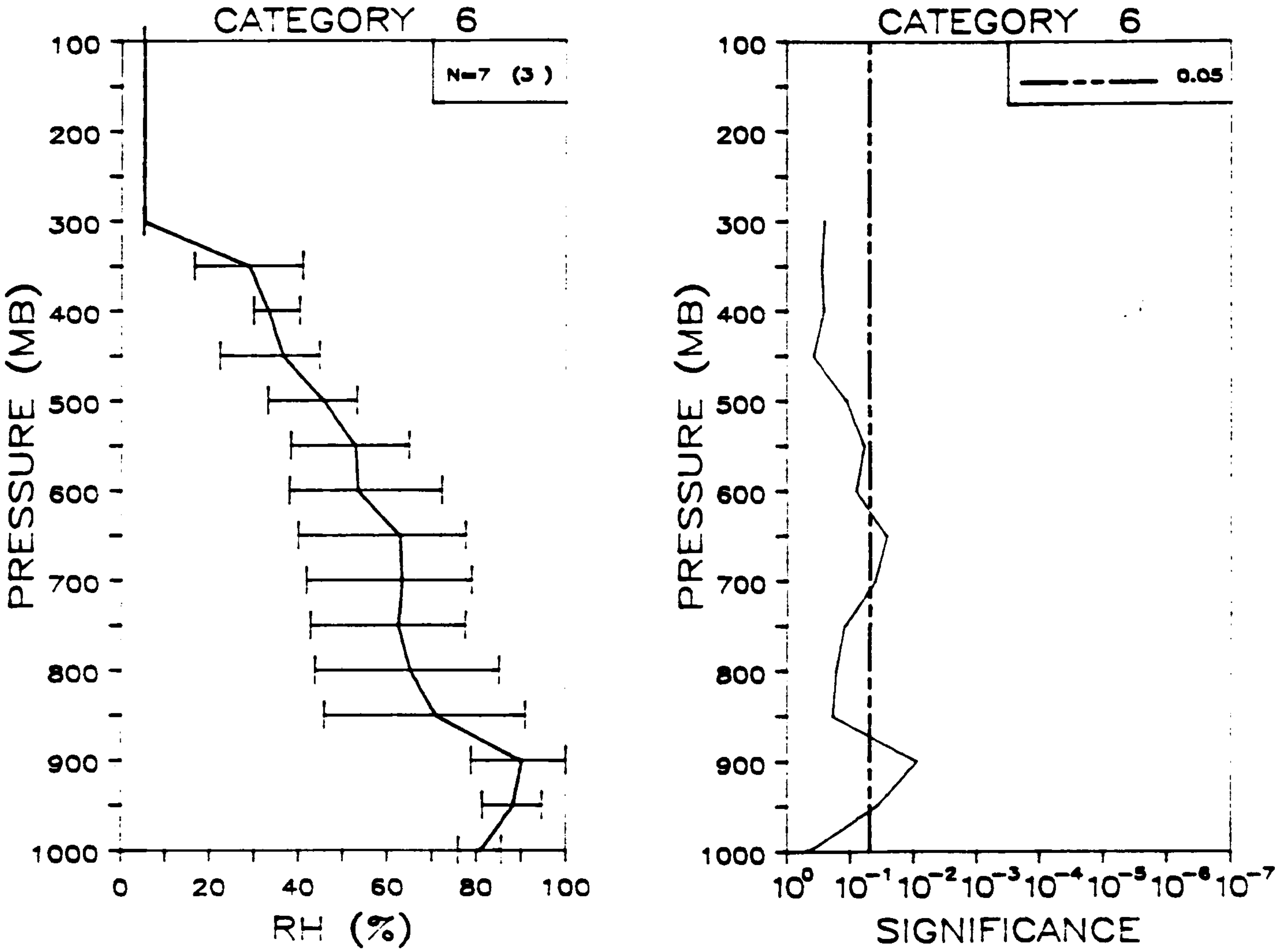

FIG. 7. Same as in Fig. 2 but for Category 6 (altocumulus [chaotic]).

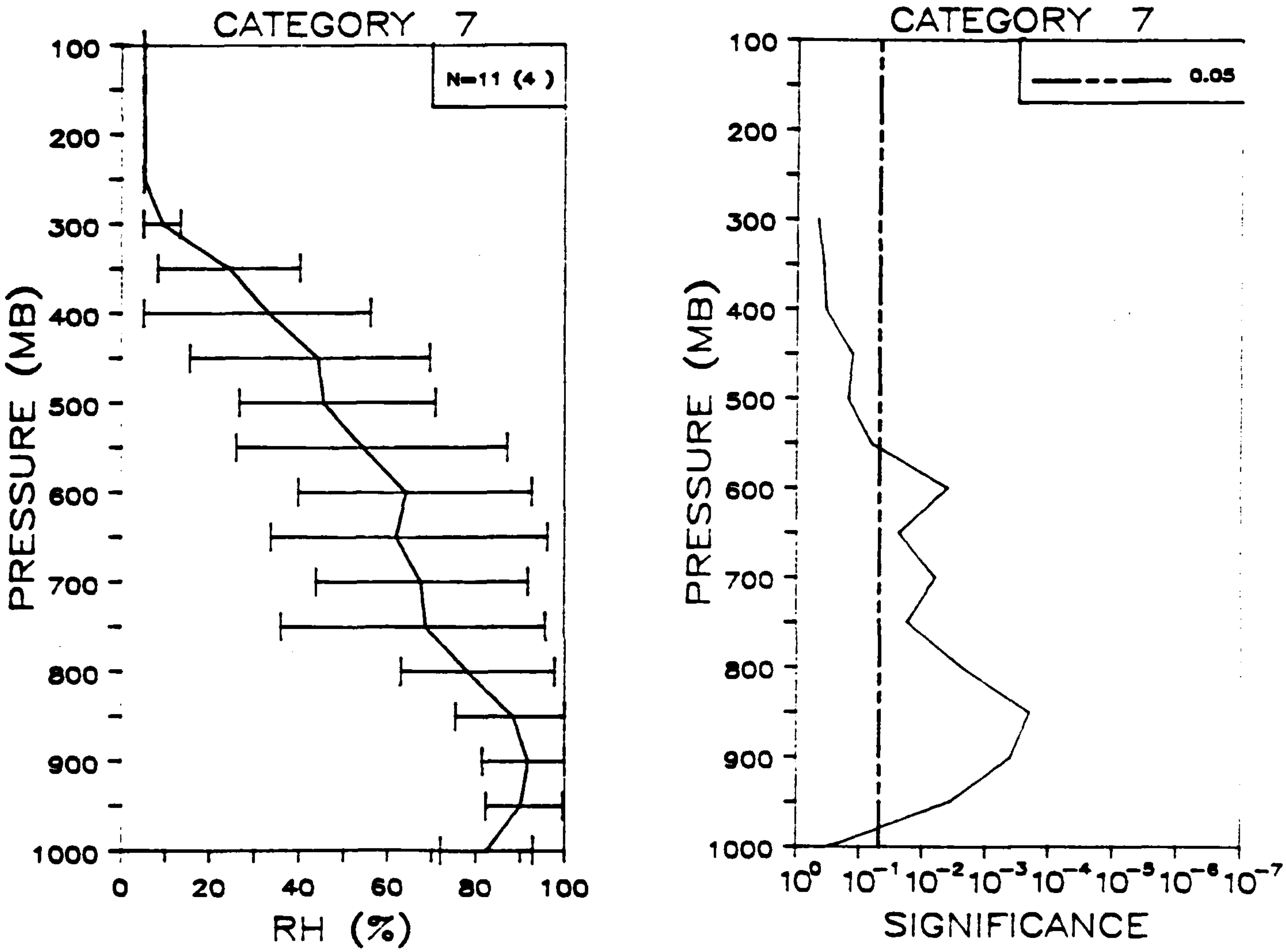

FIG. 8. Same as in Fig. 2 but for Category 7 (altostratus [organized]).

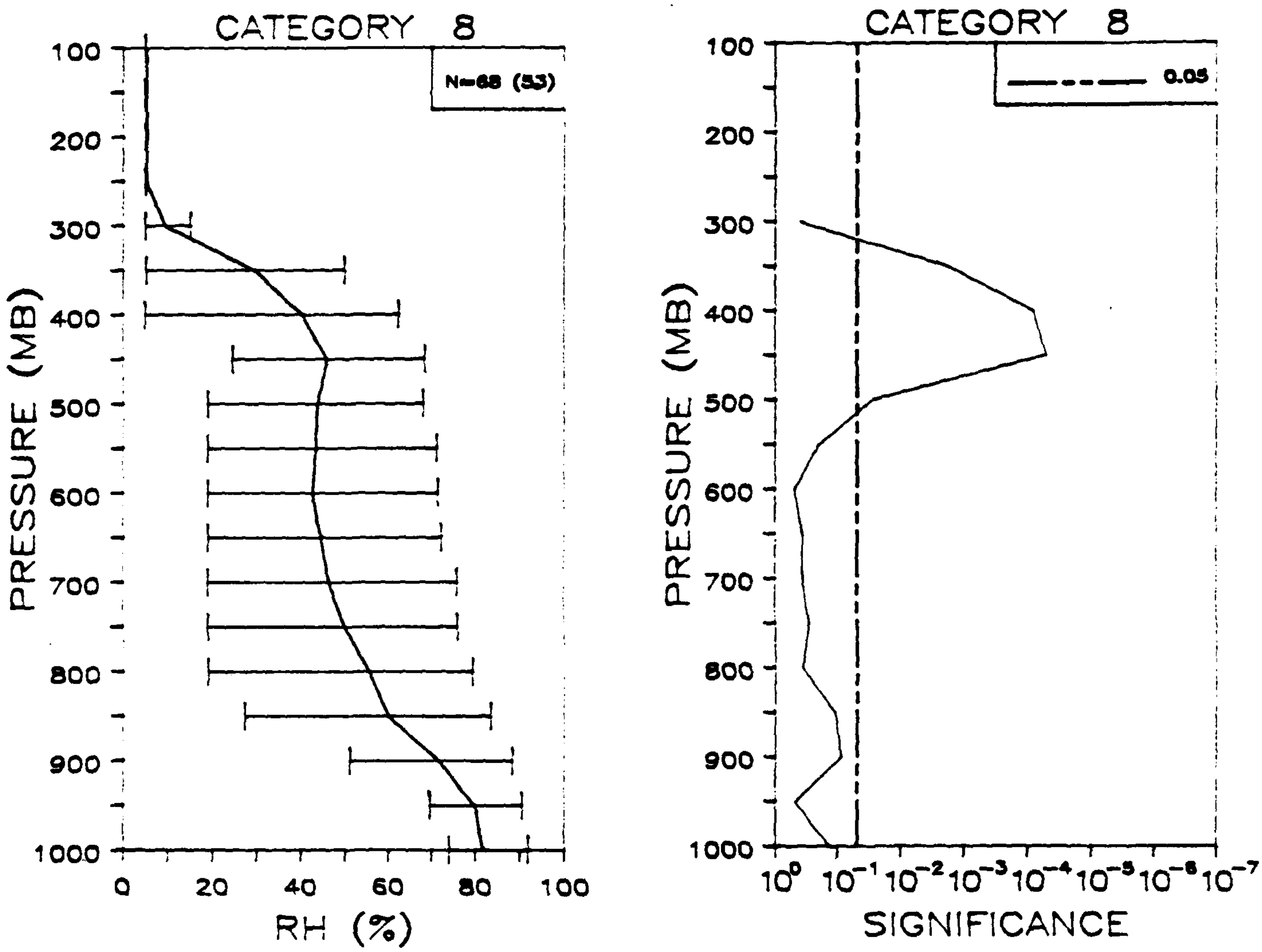

FIG. 9. Same as in Fig. 2 but for Category 8 (thin cirrus).

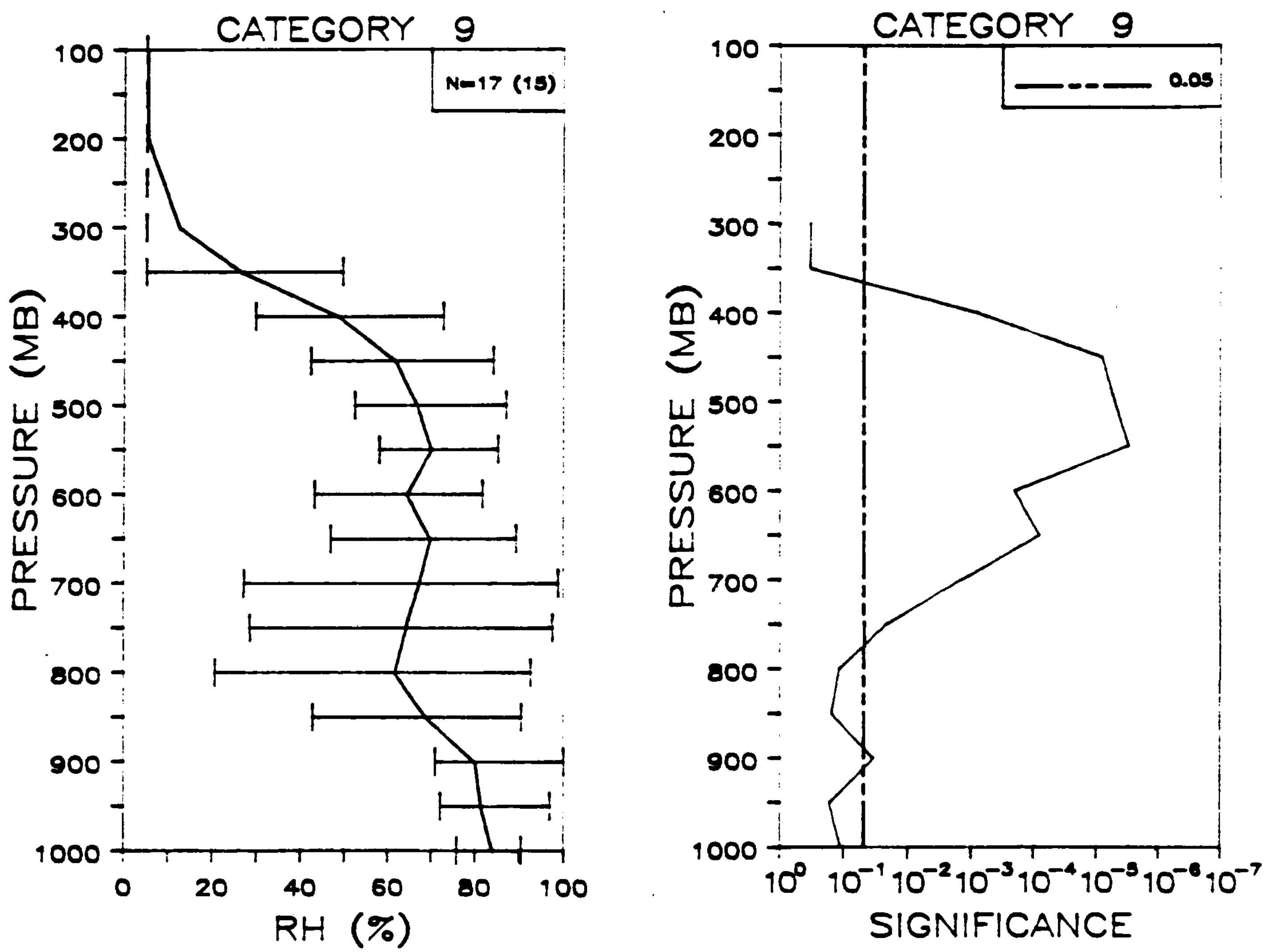

FIG. 10. Same as in Fig. 2 but for Category 9 (thick cirrus).

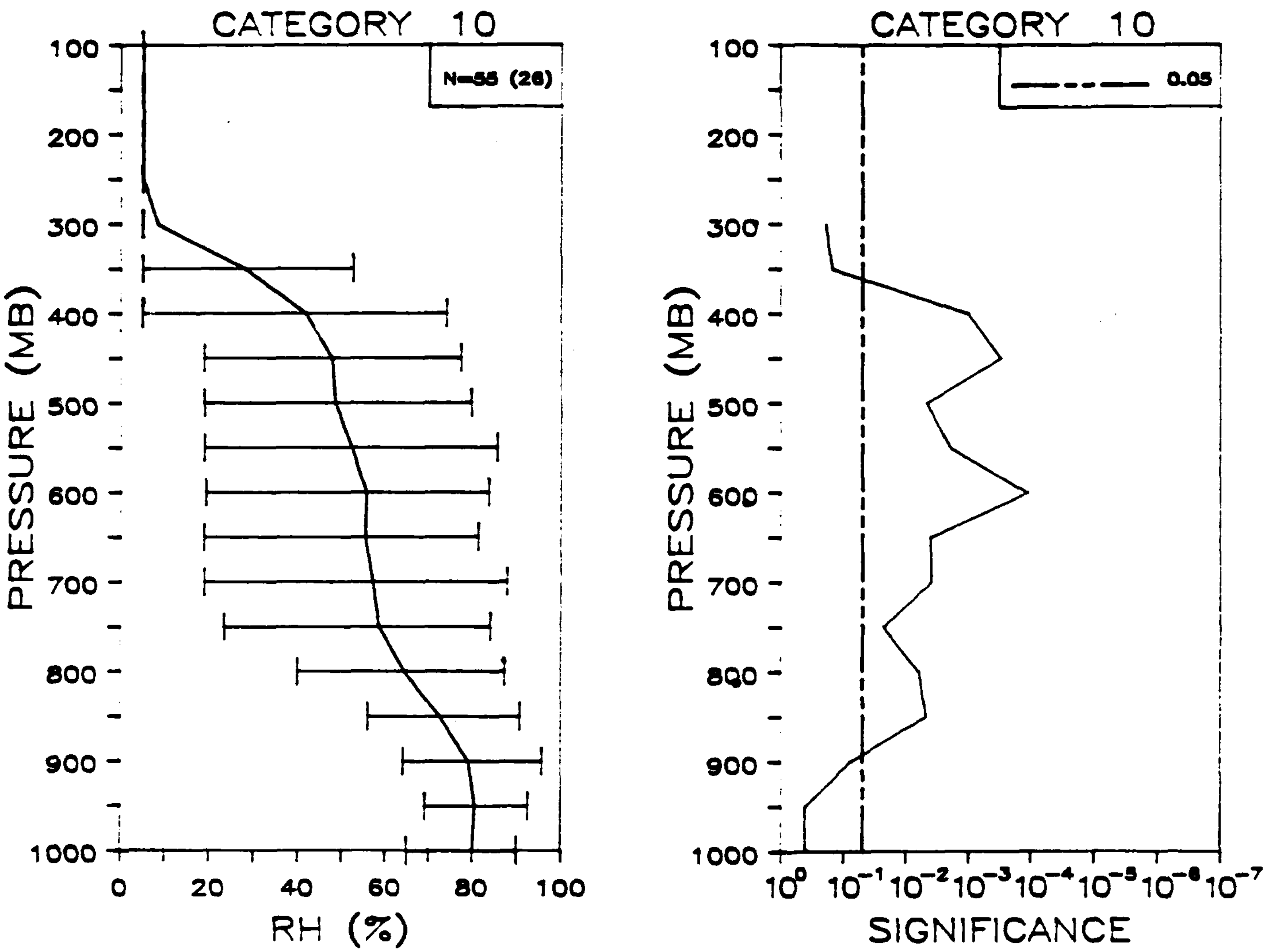

FIG. 11. Same as in Fig. 2 but for Category 10 (chaotic low, mid, and high clouds).

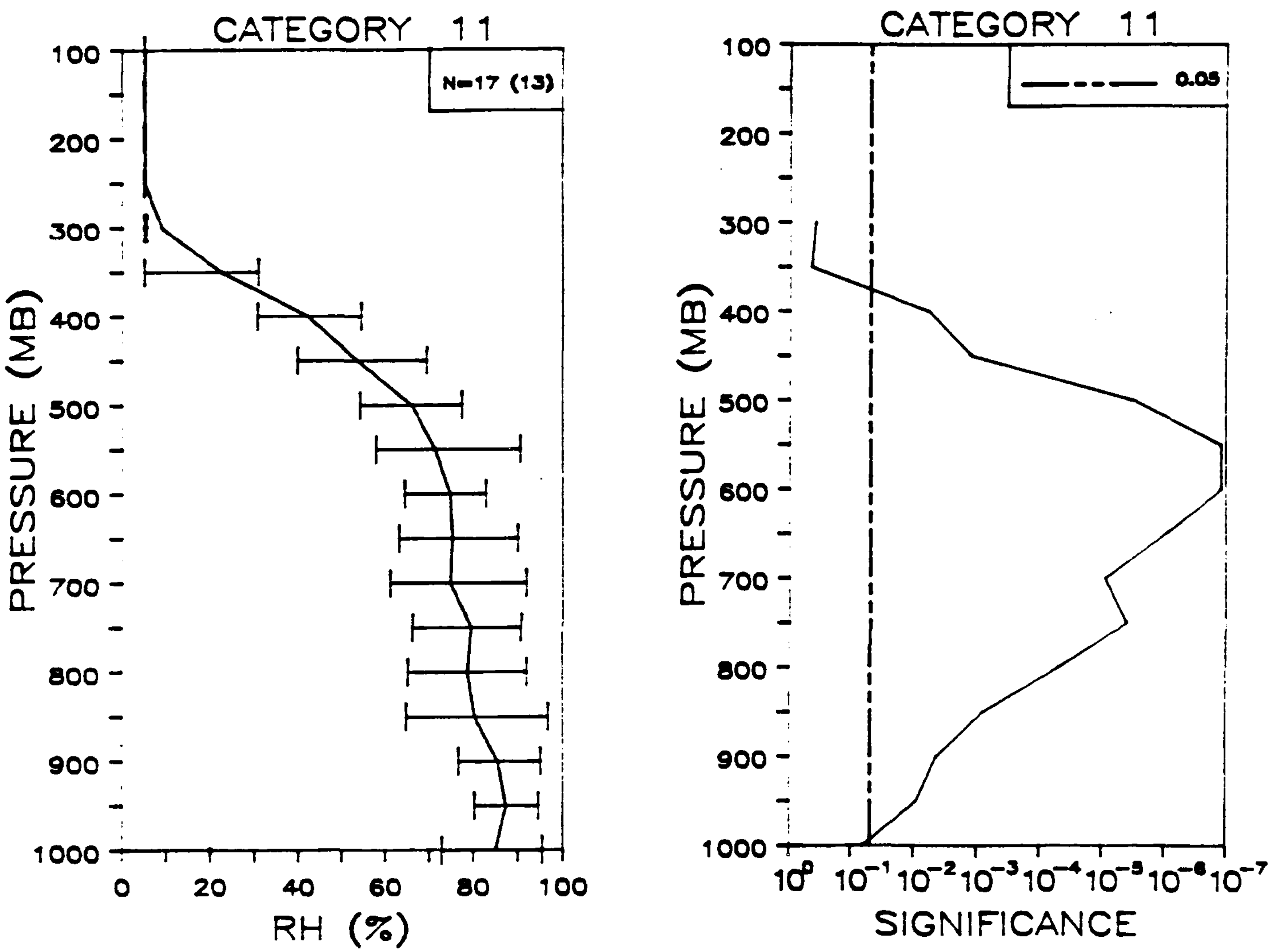

FIG. 12. Same as in Fig. 2 but for Category 11 (organized low, mid, and high clouds).

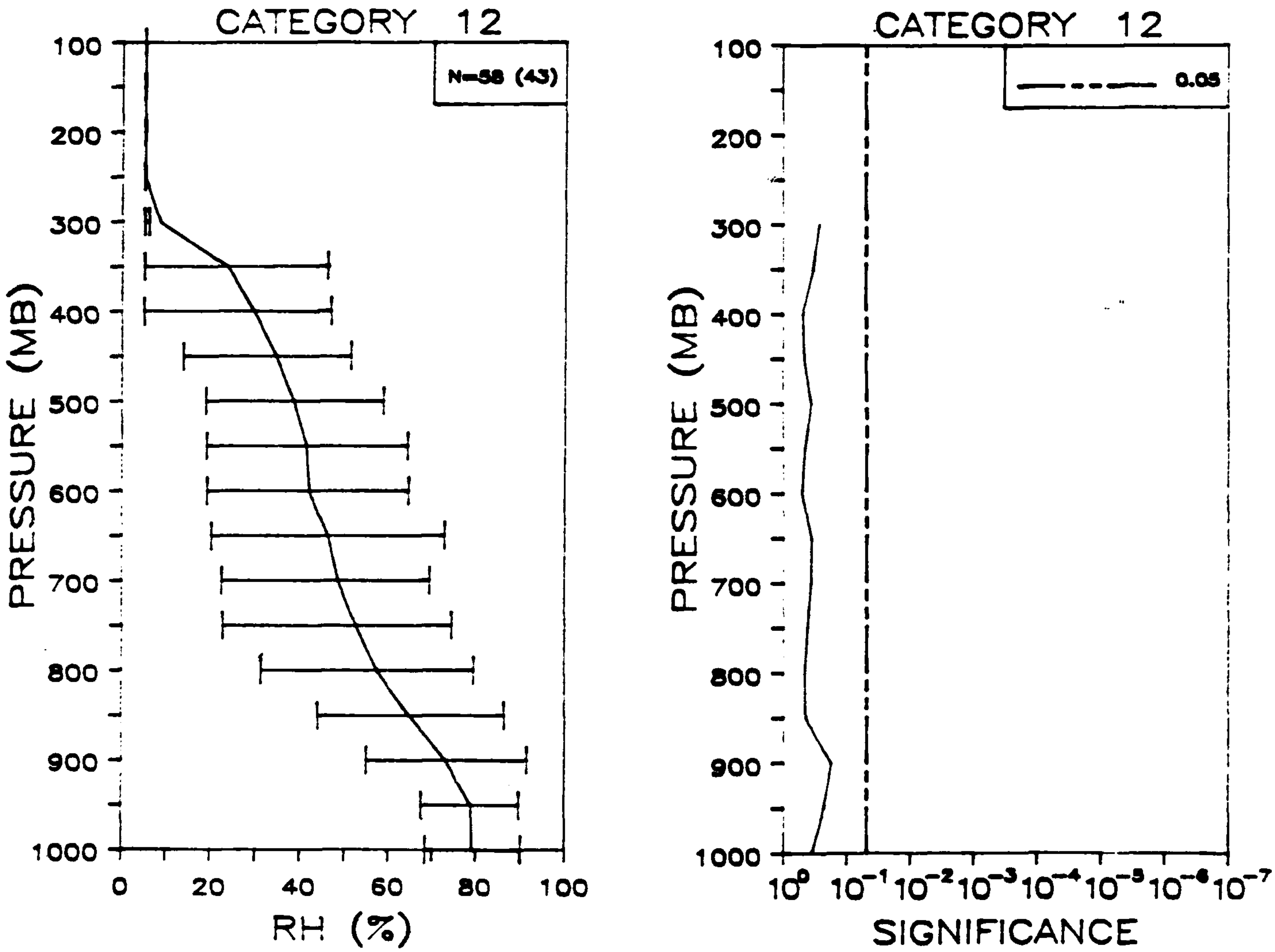

FIG. 13. Same as in Fig. 2 but for Category 12 (undecided).

on the figures) means that the probability is 5 percent that the given rank-sum discrepancy between the category and the ensemble is due to chance. The smaller the significance value the more significant the difference between the category and the ensemble.

In all but three of the categories (categories 6, 8, and 12) at least half of the levels showed a significance of 0.05 or better. Category 6 (disorganized mid clouds) was the most infrequent category with only seven soundings used in the composite. Due to this small sample the composite and the significance values may not be representative. (The same may also be true of category 7 [organized mid clouds] which had only eleven soundings). Although category 8 (thin, high clouds) has little significance from 1000-550 mb, it does have considerable significance from 500-350 mb. This distribution makes sense physically since the high clouds would be found somewhere within these upper levels. It also makes sense that category 12 (undecided) has very little significance since it is a composite of all those cases in which the analyst could not determine a category.

The significance values in Figs. 2-13 show that the composites have significant differences when compared with the rest of the sample. Significance values were also computed to determine the significance of one composite when compared to another composite. Due to the large number of comparisons (66) the values are not presented graphically level by level. Instead values are presented in Table 4. Two values are given for each comparison. The first value is the significance value for the comparison as a whole. This value was computed by averaging the test scores for each of the 15 pressure levels and determining the significance for this average score. The second value (in parenthesis) is the number of pressure levels with a significance of 0.05 or better. For example, the comparison of category 1 (clear) versus category 2 (stratus) shows a signicance value of 0.1235 for the comparison as a whole (the average of all 15 levels), and that 4 of the 15 levels have significance values of 0.05 or better. Only 13 of the 66 comparisons had fewer than five levels with significance values of 0.05 or better.

In general most of the comparisons show a considerable amount of significance when compared to each other. Two of the comparisons which showed very little significant difference were 2 (stratus) versus 3 (stratocumulus), and 9 (thick cirrus) versus 11 (thick, organized multi-level clouds). The similarity in 2 and 3 is understandable since they are so closely related physically. The similarity between 9 and 11 is not so easily understood. It is most likely the result of errors in the satellite image analysis, i.e. analyzing multi-layered cases as thick cirrus. This possibility illustrates the limitations of both the bogusing technique and its development when based on subjective satellite image analysis.

Table 4.
Significance
(Number of Levels with 0.05 or Better)

	1	2	3	4	5	6	7	8	9	10	11
2	.1235 (4)										
3	.1007 (6)	.1912 (2)									
4	.0763 (5)	.0173 (6)	.0219 (8)								
5	.0068 (11)	.0006 (13)	.0012 (13)	.0314 (8)							
6	.0148 (12)	.0347 (9)	.0540 (8)	.0276 (8)	.0544 (6)						
7	.0075 (11)	.0141 (10)	.0204 (10)	.0056 (13)	.0168 (11)	.2643 (1)					
8	.0170 (9)	.0250 (10)	.0333 (8)	.0062 (10)	.0127 (7)	.1240 (3)	.0521 (8)				
9	.0013 (13)	.0041 (12)	.0038 (9)	.0014 (12)	.0049 (12)	.1481 (3)	.1628 (3)	.0221 (8)			
10	.0028 (13)	.0043 (13)	.0036 (10)	.0027 (12)	.0370 (6)	.2829 (2)	.1404 (4)	.0897 (8)	.1294 (4)		
11	.0001 (13)	.0007 (13)	.0028 (11)	.0001 (14)	.0005 (15)	.0812 (5)	.1691 (1)	.0035 (10)	.2518 (0)	.0374 (9)	
12	.0271 (11)	.0272 (10)	.0551 (7)	.0349 (9)	.0296 (6)	.1190 (4)	.0468 (8)	.1812 (2)	.0138 (9)	.0665 (6)	.0014 (12)

4. DISCUSSION AND SUGGESTIONS

Although the composites are statistically significant, the question remains as to whether they are physically significant.

and if they would produce significantly different results if implemented in a numerical model initial analysis. The second question (model impact) will not be addressed here, but should be explored in the future. The first question (physical significance) will be discussed. The trend from dry to moist and the vertical levels with relative humidity maxima seem to qualitatively fit the worded descriptions. But the moistest relative humidity value in any of the composites is 92 percent and that occurs only once. The next three highest values are only 90 percent. Obviously in the real atmosphere, when there are significant cloud layers present, relative humidity at or near 100 percent would be observed.

Four possible explanations for the lack of relative humidity values near saturation in the composites are: 1) error in the satellite image analysis, 2) inherent spatial variability of moisture in the atmosphere, 3) radiosonde measurement error, and 4) underestimated relative humidities because saturation vapor pressure for ice is less than it is over liquid water. Errors due to 3) and 4) may be present in any radiosonde measurement and thus even in model initial analyses derived in a data rich region. Their inclusion in the bogusing composites does not add any additional error to the analyses when compared to areas using real-time radiosonde data.

In regards to the first explanation, satellite image analysis error, there are many factors which could contribute to this type of error. The first is simply the subjective nature of the analysis. For example, in Garand (1988), two satellite image analysts, considered to be experts in the field, agreed only 37 percent of the time on a strict basis, and only 55 percent of the time if their second choice was considered when using a 20-category cloud classification scheme (a study is currently underway at Point Mugu to study the differences between analysts using the categorization scheme presented in this paper).

Another contributing factor in this type of error is the quality of the satellite imagery used. As stated earlier, NOAA-2 polar orbiting satellite infrared and visual image mosaics for the Northern Hemisphere were used in this study. Unfortunately, the resolution of the imagery was somewhat limiting due to the large area contained in the image. Also, the satellite pass over the sounding point was as much as six hours off from the sounding time. In general only those soundings taken within three hours of the satellite pass were used. The exception was when very little synoptic change was observed between images. In some cases even when the soundings were within two to three hours of the satellite pass, speculation had to be made on the movement, development, or dissipation of cloud features near the sounding point. This was particularly true in the case of narrow frontal zones in the vicinity of the sounding point. A new data base of higher quality imagery taken within one hour of the sounding time could significantly reduce this type of error. Efforts are currently underway to obtain such a data set.

The second explanation, inherent spatial variablity, is almost certainly a reason for the lack of relative humidities near saturation in the composites. This variability manifests itself in two ways. First, cloud patterns do not always fit into a finite number of categories. There may be enough similarity from one case to the next to warrant having distinct groupings, but there will always be cases that do not fit the categorization. For example, 58 of the 471 soundings used in this study were considered unidentifiable under the scheme presented in this paper. Lyons (1986b), in determining composites for the Northeast Pacific, tried to overcome this problem by selecting only "classical" examples for each of his categories. As a result, his composites were based on only two to ten soundings, thus leaving open the question of their validity in representing the varied conditions found in the atmosphere.

The second manifestation of spatial variability is in the vertical. Even within easily identifiable categories there will be vertical variations in the height and thickness of the cloud layers. This variation produces thicker but drier moist layers in the composites. The total integrated moisture within the column of air may be similar for the composite and the individual cases, but no cloud layer would be identifiable in the composite. This could present a problem in a numerical model where parameterizations of precipitation and radiation processes are not used until the relative humidity nears saturation. One possible suggestion to overcome this problem of vertical smoothing would be to determine the distribution of cloud height and thickness based on the sounding relative humidities and create a saturated cloud layer at the most frequently occurring levels with an average thickness taken from the data. Moisture would then have to be taken out in other areas in order to preserve the same amount of total moisture content within the column. This technique will be investigated more fully in the future.

5. SUMMARY

Vertical moisture profiles for use in satellite bogusing of moisture into numerical model initial analyses were presented for the North Atlantic Ocean region. The profiles were based on a 12 category cloud classification scheme and computed from 471 soundings taken in the North Atlantic during January, July, and October of 1974. Assignment of soundings to one of the cloud categories was done by subjective analysis of Northern Hemisphere infrared and visual satellite image mosaics taken from the NOAA-2 polar orbiting satellite. Composites for the categories and results of statistical significance tests were presented. The composites appeared to vary appropriately according to their different descriptions. The significance tests showed that the vast majority of the composites were statistically significant when compared to the sample and when compared to each other.

A lack of relative humidity values near saturation was considered cause for concern. Errors in satellite image analysis, inherent spatial variability of moisture in the atmosphere, radiosonde measurement error, and differences in saturation vapor pressure over liquid water and ice were considered as possible reasons for the lack of relative humidity values near saturation in the composites. More highly resolved satellite imagery closer to the sounding times was suggested as a possible way to significantly decrease this error. A technique for retaining cloud layers in the compositing process was suggested as a possible means of reducing the smoothing of relative humidity in the vertical due to vertical moisture variability.

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